

# Multiwavelength Challenges in the *Fermi* Era

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**ABSTRACT.** The gamma-ray surveys of the sky by AGILE and the *Fermi Gamma-ray Space Telescope* offer both opportunities and challenges for multiwavelength and multi-messenger studies. Gamma-ray bursts, pulsars, binary sources, flaring Active Galactic Nuclei, and Galactic transient sources are all phenomena that can best be studied with a wide variety of instruments simultaneously or contemporaneously. From the gamma-ray side, a principal challenge is the latency from the time of an astrophysical event to the recognition of this event in the data. Obtaining quick and complete multiwavelength coverage of gamma-ray sources of interest can be difficult both in terms of logistics and in terms of generating scientific interest.

## 1. Introduction - The Multiwavelength Revolution

The process of astrophysical research has changed dramatically in the past 30 years, and the inclusion of multiwavelength studies has been an important aspect of that change. As an example of the growing importance of studies that reach beyond a single wavelength, consider this simple literature search using NASA ADS (<http://adsabs.harvard.edu/ads-abstracts.html>). The search was for the word “Multiwavelength” in titles for each of four years spanning three decades. The result is shown in Table 1.

TABLE I  
Papers with “Multiwavelength” in the Title

Year	Papers
1976	0
1986	2
1996	58
2006	97

Even considering the normal growth of scientific publications, the increase in multiwavelength research has been dramatic. Many astrophysicists have come to recognize the value of multiwavelength research.

Several enabling technologies have made this multiwavelength revolution possible, including:

- Availability of Observational Resources

Today ground-based and space-based observatories cover much of the electromagnetic spectrum and related multi-messenger fields such as neutrinos and gravitational waves. Just 27 years ago, in 1982, the capabilities for multiwavelength studies were far more limited, as illustrated in Table II.

Research opportunities for multiwavelength astrophysics were sparse. Data quality was more suited for exploration than detailed study in some bands. Few all-sky surveys were available for reference.

TABLE II  
Multiwavelength Resources in 1982

Wavelength	Status
Radio telescopes	VLA had been open just 2 years, VLBA had not been started
Sub-mm	Just getting started
Infrared	No satellites (IRAS was launched in 1983), IR detectors had limited capability
Optical	Largest telescopes: Hale 5 m, Soviet 6 m, few CCDs
Ultraviolet	IUE (a bright spot)
X-ray	Hakucho Japanese satellite
Gamma-ray	COS-B was turned off in that year
TeV	Whipple Observatory was just getting started

By contrast, just the gamma-ray part of the spectrum is now viewed by an array of instruments. In space, examples include Swift, INTEGRAL, AGILE, and *Fermi*. Ground-based facilities operating at higher energies include ARGO-YBJ, CANGAROO, H.E.S.S., Milagro/HAWC, MAGIC, and VERITAS.

- Improvements in Communication

In parallel with advances in observational capabilities has come the explosion of high-speed communication. Table III shows some milestones that have marked the growth of fast, easy exchange of information.

TABLE III  
Some Important Dates in the Development of Fast Communication

Year	Status
1977	111 computers on ARPANET, forerunner of the Internet. Most information exchange was on paper.
1981	First IBM Personal Computer
1983	TCP/IP protocol; SENDMAIL program started; e-mail became practical.
1988	NSFNET backbone upgraded to 1.5 Mbps
1990	Tim Berners-Lee and the first Web server
1993	Mosaic Web browser
1999	Wi-Fi (IEEE 802.11 standard) wireless

The ability to exchange large quantities of information rapidly has been essential to the growth of multiwavelength astrophysics. Observers and analysts are not constrained by physical location.

- Growth of Consolidated Information Resources

Resources like ADS, NED, Simbad, ASDC, HEASARC, and others facilitate rapid review of existing coverage of sources. Scientists can now almost instantaneously survey archival results for nearly any cataloged object. The ability to compare past and present results across the spectrum opens new possibilities for quick reaction to transient events, as well as long-term comparisons of source behavior.

## 2. Multiwavelength Opportunities - the Gamma-ray Perspective

Among the flood of new results coming from current gamma-ray telescopes, many involve multiwavelength (MW) studies. Because other papers at this conference will describe details, I just list some and note their connection to other wavelengths:

1. Gamma-ray bursts - *Fermi* LAT and GBM, AGILE Grid and Super-AGILE, X-ray counterparts for positioning; redshift measurements in optical.
2. Pulsars, using radio and X-ray data for timing and providing information to radio observers.
3. AGN studies - especially ATel flare reports, MW correlations and broad-band spectral studies.
4. Binaries - timing and spectral comparisons with X-ray and TeV.
5. New source classes - including starburst galaxies, narrow line Seyfert quasars.
6. Diffuse radiation (and associated dark matter searches) - models are built on MW data.

A few specific examples illustrate how the MW process leads to greater understanding:

- PSR J1741-2054 is a radio pulsar found based on gamma-ray timing (Camilo et al 2009). A bright *Fermi* LAT point source was the first step. An analysis of the LAT timing discovered gamma-ray pulsations. A follow-up observation with the Swift X-Ray Telescope (XRT) found an X-ray source that gave better position information than could be determined from the LAT image. Using the LAT timing information and the Swift location allowed archival analysis using Parkes radio data and a deep search using the Green Bank Telescope that found the radio pulsar.
- PMN J0948+0022 is known as a narrow-line quasar or a radio-loud Narrow-Line Seyfert 1 galaxy, a somewhat different class than the blazars that are regularly seen in gamma rays. Contemporaneous observations combining the LAT data with Swift (X-ray, UV, and optical) and Effelsberg (radio) results revealed a Spectral Energy Distribution that indicated the presence of a relativistic jet in this source, similar to those found in blazars (Abdo et al. 2009).
- Using the public light curves made available by the LAT team (at the *Fermi* Science Support Center Web site <http://fermi.gsfc.nasa.gov/ssc/>), Bonning et al. (2009) studied simultaneous multiwavelength variability of blazar 3C454.3 using Small and Moderate Aperture Research Telescope System (SMARTS) telescopes for optical and ultraviolet observations and X-ray data from the Swift satellite. They found excellent correlation, with a time lag less than a day, an important parameter for interpreting this blazar in terms of an external Compton model.

These few examples demonstrate some of the ways gamma-ray results enhance scientific understanding when combined with observations and analysis from other wavelengths. Because the position uncertainties for gamma-ray sources are still large compared to those at many other wavelengths, unidentified gamma-ray sources are inherently subjects for multiwavelength studies, depending on timing, spectral, and physical modeling to determine what objects produce the gamma rays.

## 3. Multiwavelength Challenges: What Can Be Done?

Despite the tools and resources now available for multiwavelength studies, the *Fermi* LAT presents some challenges in terms of making the best scientific use of the gamma-ray data. Three of these issues are described in the sections below.

### 3.1. The Challenge of Time

Gamma-ray bursts (GRB), thanks to the the Gamma-ray bursts Coordinates Network (GCN, <http://gcn.gsfc.nasa.gov/>), offer a paradigm for rapid response to transient astrophysical events. The success of the GCN originates in part from the intensity of GRB, which can be recognized automatically with high confidence in satellite detectors. The time for disseminating initial information about a burst is not generally governed by the actual detection but rather by the speed of communication. Multiwavelength studies can often begin within seconds of the initial detection.

The situation for other gamma-ray sources is more complicated, because none of them approaches the instantaneous brightness of a GRB. Nevertheless, dramatic changes in flux have been seen on time scales of a day or less (e.g. PKS 1502+106, Abdo et al. 2010). On-board analysis of such sources by the LAT is not practical, and so the response depends on both communication and analysis. The *Fermi* LAT data are stored onboard and transmitted through the Tracking and Data Relay System to the ground in batches, not continuously. This process introduces some delay, as does the data reduction to extract the gamma-ray event candidates and compare the gamma-ray sky with its previous appearance. Half a day can pass before a flare is discovered.

The LAT team has taken several steps to minimize the latency in reporting events of multiwavelength interest:

- Automation - Much of the data handling process is now automated, and efforts continue to streamline the procedures. The internal LAT team analysis process automatically generates lists of sources detected on 6 hour, 1 day, and 1 week time scales. The analysis pipeline also now produces preliminary flux values for over 40 sources of interest routinely, and these results are posted daily at <http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl.lc/>.
- Dedication - The LAT team has a group of scientists called Flare Advocates or Skywatchers, who examine the automatically produced analysis results as soon as they appear. By applying scientific expertise at this early stage, the process optimizes the response to findings of astrophysical interest while minimizing any reaction to statistical fluctuations of steady sources.
- Communication - Flare Advocates use three avenues to share results quickly about activity in the gamma-ray sky. The first is the use of Astronomer's Telegrams, <http://www.astronomersteletgram.org/>, over 40 of which have been issued by the LAT team for quickest reporting of results. The second is a multiwavelength mailing list, *gammamw* (<https://lists.nasa.gov/mailman/listinfo/gammamw>), which is used to contact scientists directly about gamma-ray multiwavelength news. Anyone interested is welcome to join this list. The third approach is the Fermi Sky Blog, <http://fermisky.blogspot.com/>, which posts weekly summaries of the brightest sources in the high-energy gamma-ray sky.

### 3.2. The Challenge of Too Much Gamma-ray Data

Although the LAT is an all-sky, every-day monitor for high energy gamma rays, most telescopes at other wavelengths have much smaller fields of view and sky coverage. In addition, many telescopes have sun-angle constraints. Multiwavelength coverage of an active gamma-ray source is not assured. Two approaches are being used by the multiwavelength community to enhance the coverage of the sky:

- More all-sky or wide-field monitors are becoming available. The RXTE All-Sky Monitor in X-rays (<http://xte.mit.edu/>) has recently been complemented with the Japanese MAXI all-sky X-ray monitor on the International Space Station

(<http://maxi.riken.jp/top/>). In optical, the Palomar Quest program regularly surveys a large area (<http://www.astro.caltech.edu/george/pq/>), and the Pan-STARRS (<http://pan-starrs.ifa.hawaii.edu/public/>) and Skymapper (<http://msowwww.anu.edu.au/skymapper/>) programs will be surveying much of the northern and southern hemispheres repeatedly. At longer wavelengths, Planck (<http://www.rssd.esa.int/index.php?project=Planck>), Herschel (<http://herschel.esac.esa.int/>), and WISE (<http://www.nasa.gov/mission-pages/WISE/main/index>) are viewing the sky with fairly long cadence.

- Source monitoring programs have also emerged. In radio, many observers are co-operating to provide multiple-instrument monitoring of many candidate gamma-ray targets, particularly blazars. A summary of ongoing activity can be found at <http://pulsar.sternwarte.uni-erlangen.de/radiogamma/>. Similarly, optical programs like the one at the University of Arizona (<http://james.as.arizona.edu/psmith/Fermi/>), SMARTS (<http://www.astro.yale.edu/smarts/glast/>), and the GLAST-AGILE Support Program (GASP, <http://www.to.astro.it/blazars/webt/gasp/homepage.html>) observe many gamma-ray sources regularly in the optical.

A useful collection of links to multiwavelength information can be found at <https://confluence.slac.stanford.edu/a>. The LAT team greatly appreciates the ongoing cooperative activities of all these groups and welcomes other telescope teams who participate in particular campaigns.

### 3.3. The Challenge of Choosing Collaborators

With all the *Fermi* data public, along with software for analysis, anyone can undertake multiwavelength studies incorporating gamma-ray results. There may be times when contacting the LAT team could benefit such analysis, however.

Analysis of the LAT data does involve some important caveats:

- The diffuse Galactic emission is bright and highly structured. The diffuse model supplied by the LAT team has recently been updated and is likely to continue to evolve. Separating weaker sources from the diffuse Galactic emission is non-trivial. There are regions of the sky where the diffuse model has deficiencies.
- The LAT Instrument Response Functions (IRFs) have significant uncertainties at energies near 100 MeV and a non-negligible charged particle background at energies above 10 GeV. Improvements in the IRFs are expected but are not imminent. Analysis of data below 100 MeV with the current IRFs is not recommended.

Please see <http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT.caveats.html> for more details about these analysis issues.

Some suggestions about when consulting the LAT team might be beneficial:

- If you are searching for a source that is not in the LAT catalog, then it is probably weak enough that a simple analysis will not be adequate.
- If you need a detailed energy spectrum or are looking for particular spectral features, especially at very low or very high energies, the LAT team has experience with non-standard analysis.
- If you are trying to analyze the Galactic Center region, you are strongly advised not to go it alone!
- If you are interested in the most complete multiwavelength coverage, consider contacting the LAT team. The LAT team knows many cooperating groups across the spectrum who may be interested in working with you (even if you do not include the LAT team).

#### 4. Conclusion

With the public release of LAT and AGILE data, opportunities for multiwavelength studies of the gamma-ray sky are growing. Particular challenges in this new era include the need for quick responses, the difficulty of getting enough coverage for the many sources that are seen, and the question of whether to work with an instrument team. Communication continues to be a key to multiwavelength success.

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